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(54) **CRANE CONTROL SYSTEMS AND METHODS**

(75) Inventors: **William Singhose**, Atlanta, GA (US); **Chen Chih Peng**, Atlanta, GA (US)

(73) Assignee: **Georgia Tech Research Corporation**, Atlanta, GA (US)

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(51) **Int. Cl.**
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B66C 13/06 (2006.01)

(52) **U.S. Cl.**
CPC ***B66C 13/40*** (2013.01); ***B66C 13/063*** (2013.01)

(58) **Field of Classification Search**
USPC 212/272, 273, 275, 83, 97
See application file for complete search history.

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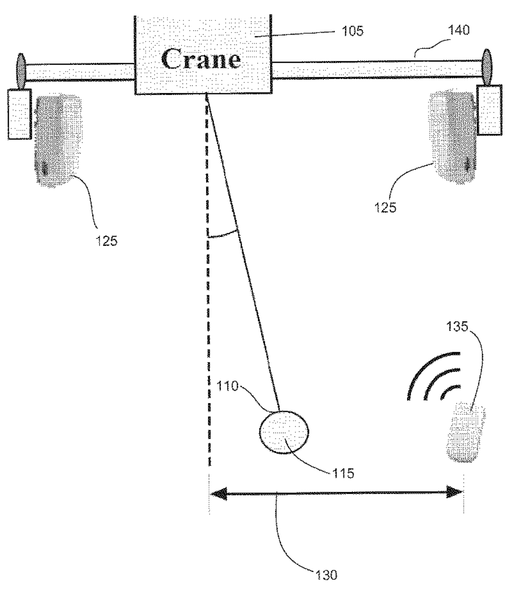
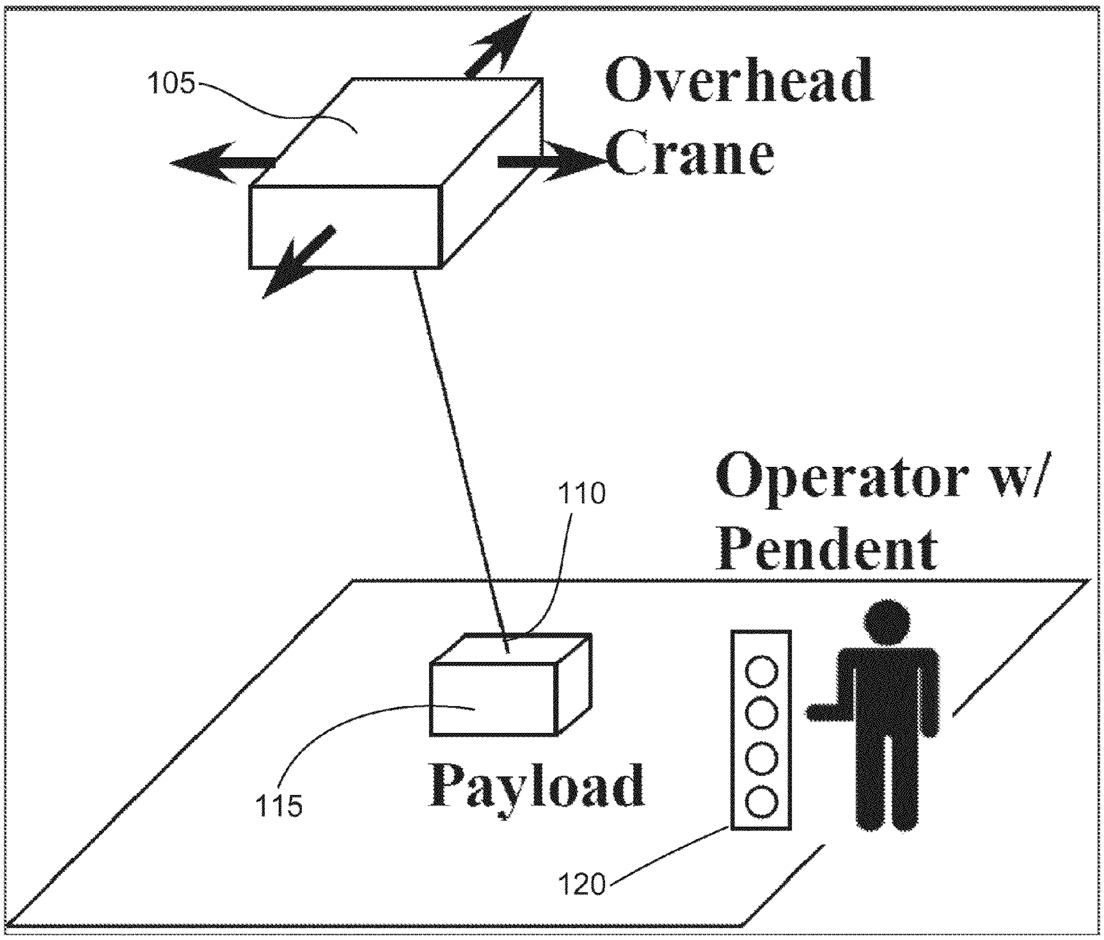
Primary Examiner — Emmanuel M Marcelo
(74) *Attorney, Agent, or Firm* — Troutman Sanders LLP; Ryan A. Schneider; Parker D. Hancock

(57) **ABSTRACT**

The various embodiments of the present disclosure relate generally to crane control systems. An exemplary embodiment of the present invention provides a crane control system comprising a real-time position-location module, an on-off controller module, and an input-shaper module. The real-time position-location module generates a position signal indicative of the distance between crane trolley and a desired location of safety. The on-off controller module maps the position signal to a velocity command signal, wherein the velocity command signal comprises instructions for the crane trolley to move in a vector relative to the desired location in at least a first velocity only if the distance between the crane trolley and the desired location is greater than a cut-off threshold **150**. The at least a first velocity is a substantially constant. The input shaper module manipulates the velocity command signal mapped by the on-off controller module to dampen payload oscillations.

28 Claims, 15 Drawing Sheets





Prior Art

Figure 1

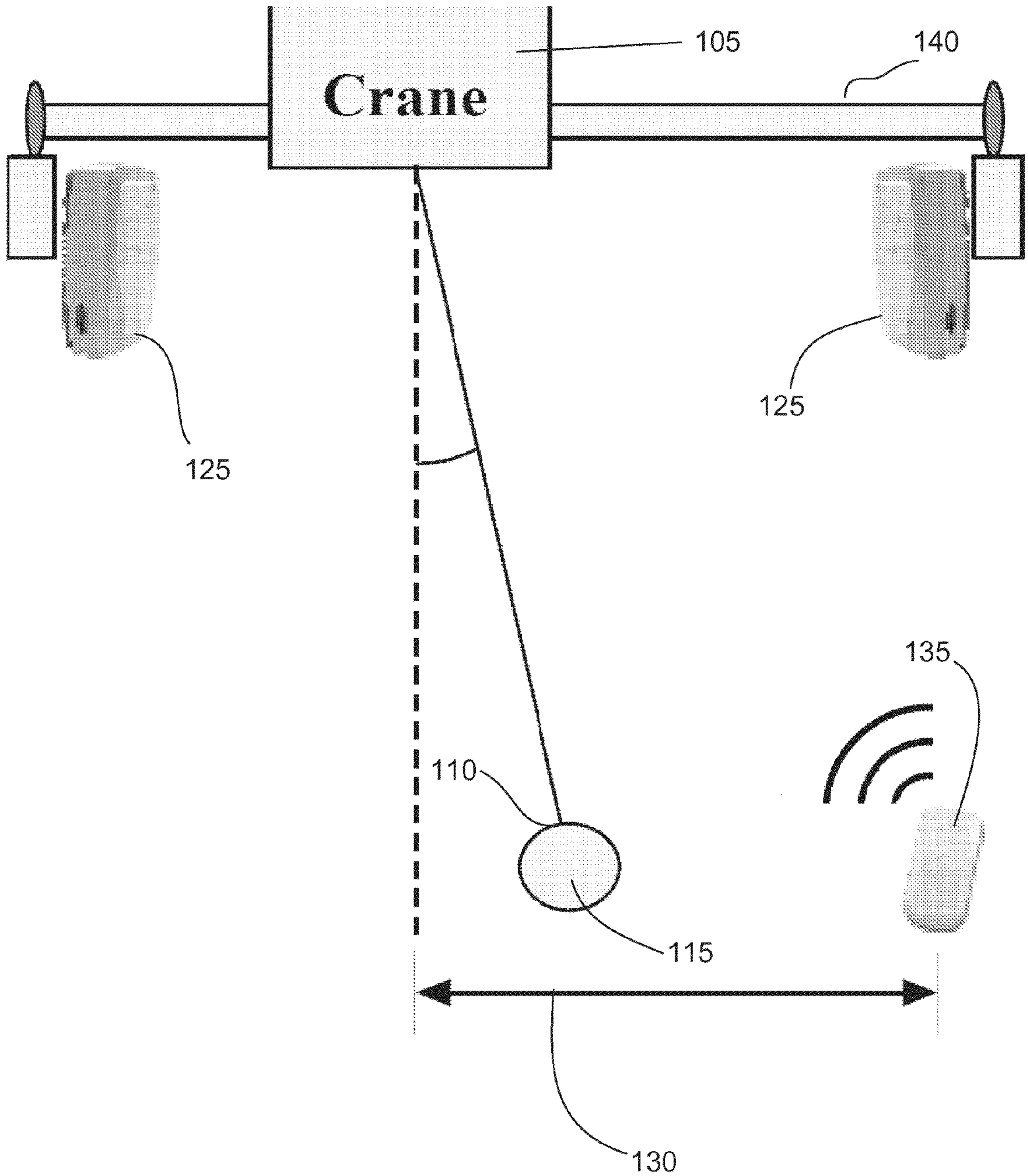


Figure 2

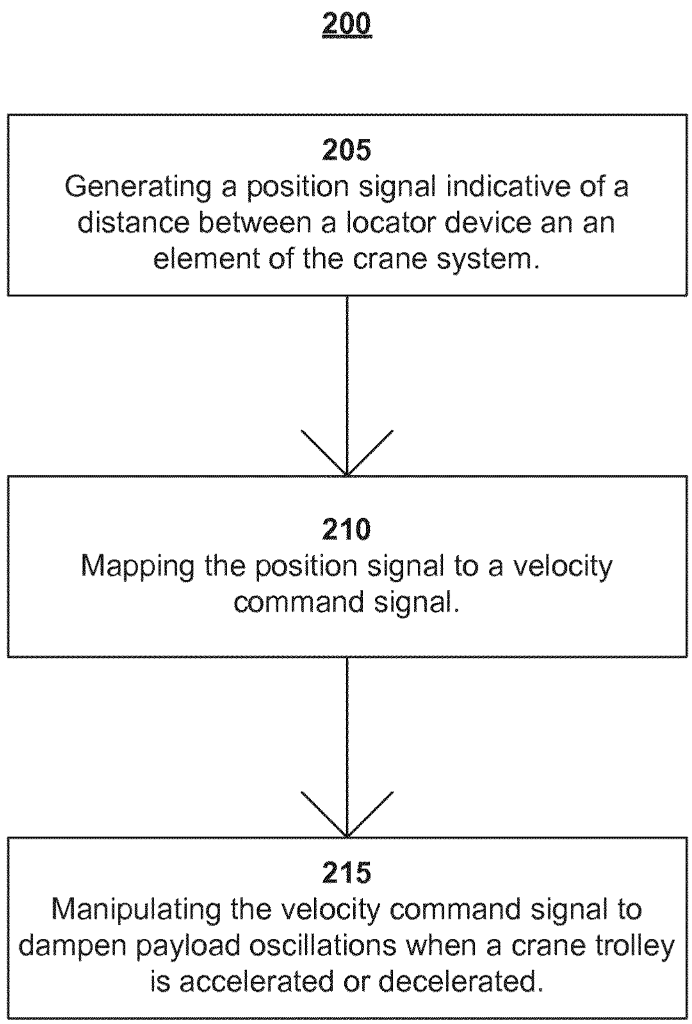

200
205
Generating a position signal indicative of a distance between a locator device an an element of the crane system.
210
Mapping the position signal to a velocity command signal.
215
Manipulating the velocity command signal to dampen payload oscillations when a crane trolley is accelerated or decelerated.

Figure 3

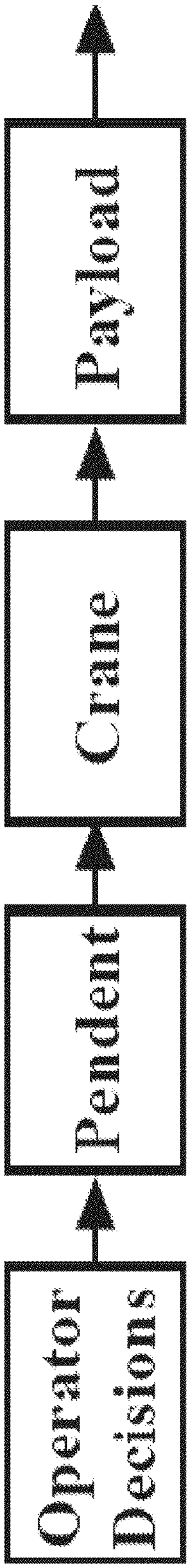


Figure 4

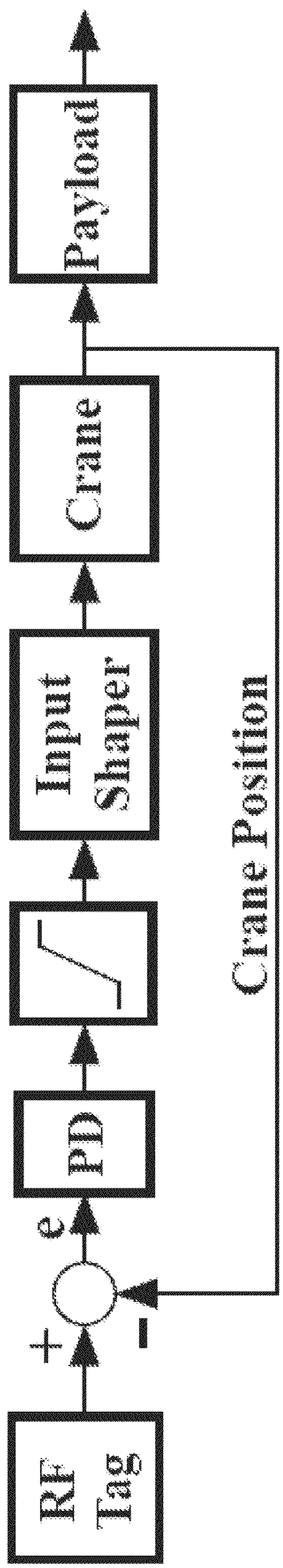


Figure 5

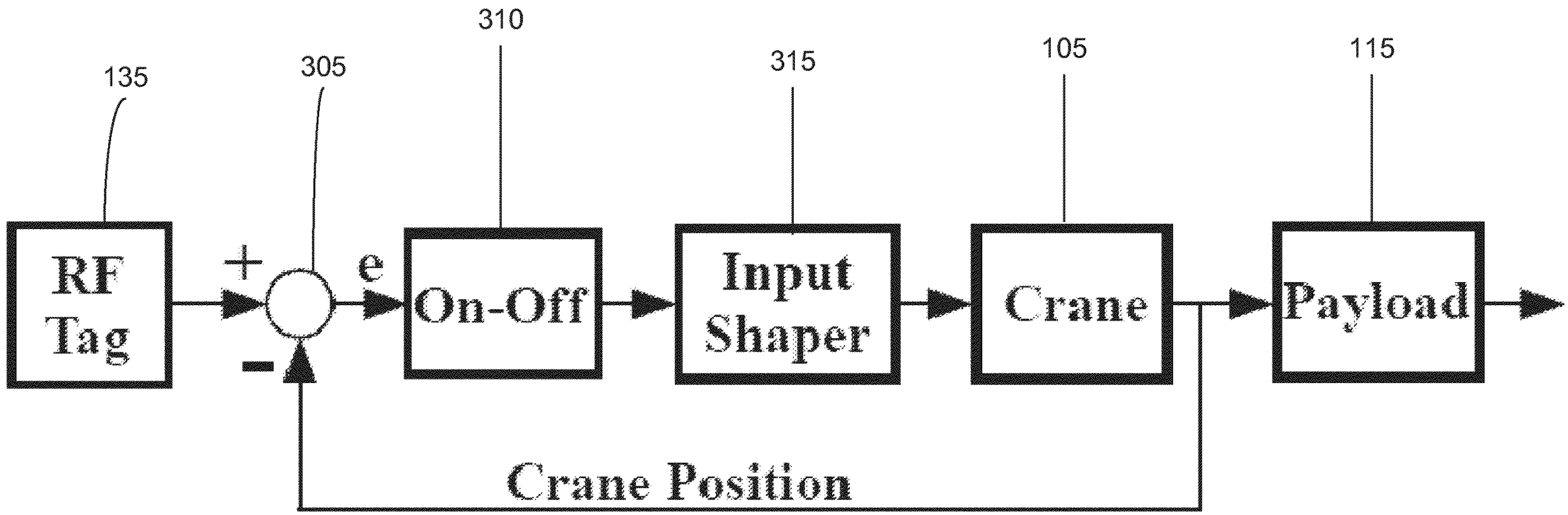

135
305
310
315
105
115
RF Tag
+
−
e
On-Off
Input Shaper
Crane
Payload
Crane Position

Figure 6

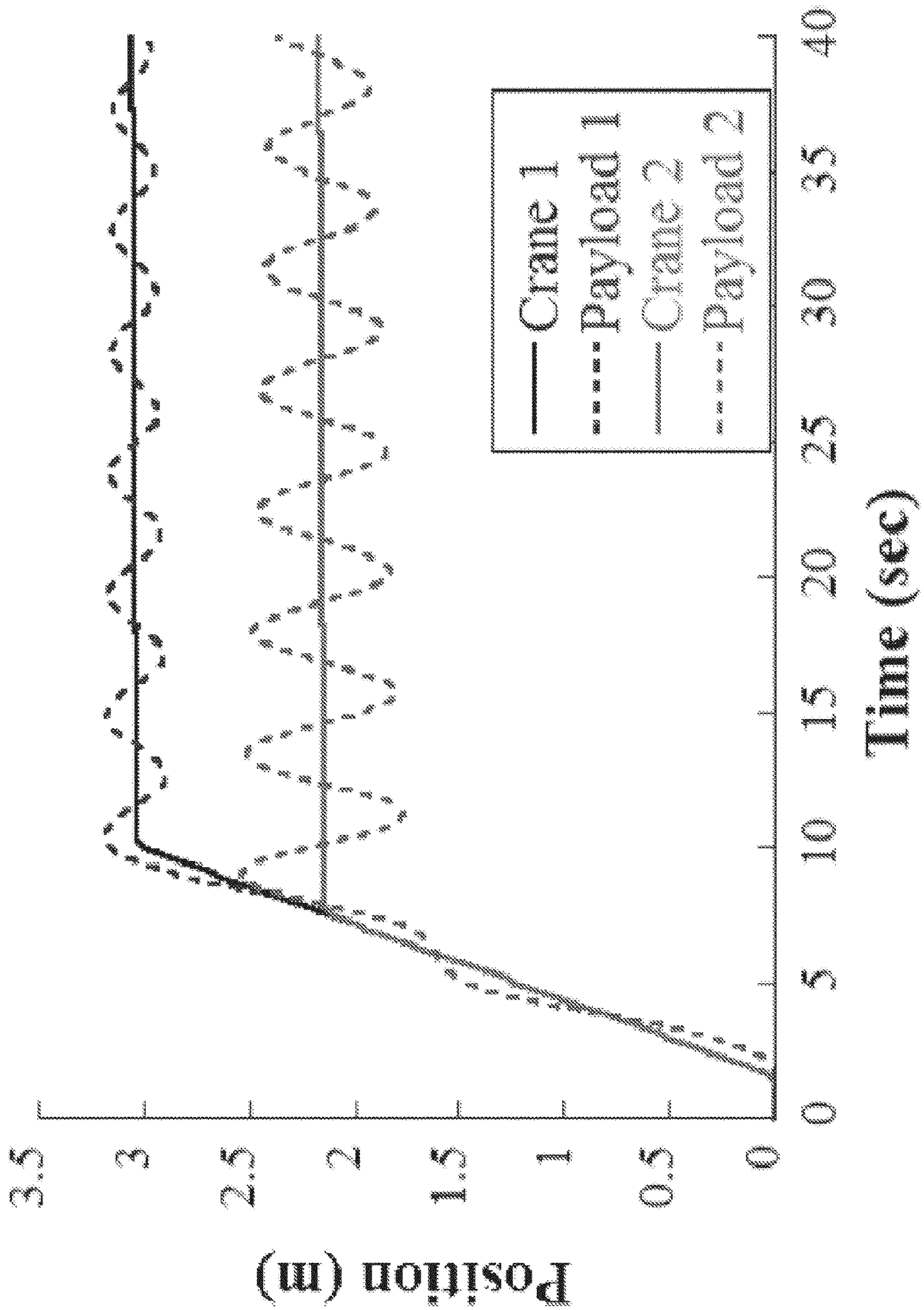

Position (m)
Time (sec)
Crane 1
Payload 1
Crane 2
Payload 2
0
0.5
1
1.5
2
2.5
3
3.5
0
5
10
15
20
25
30
35
40

Figure 7

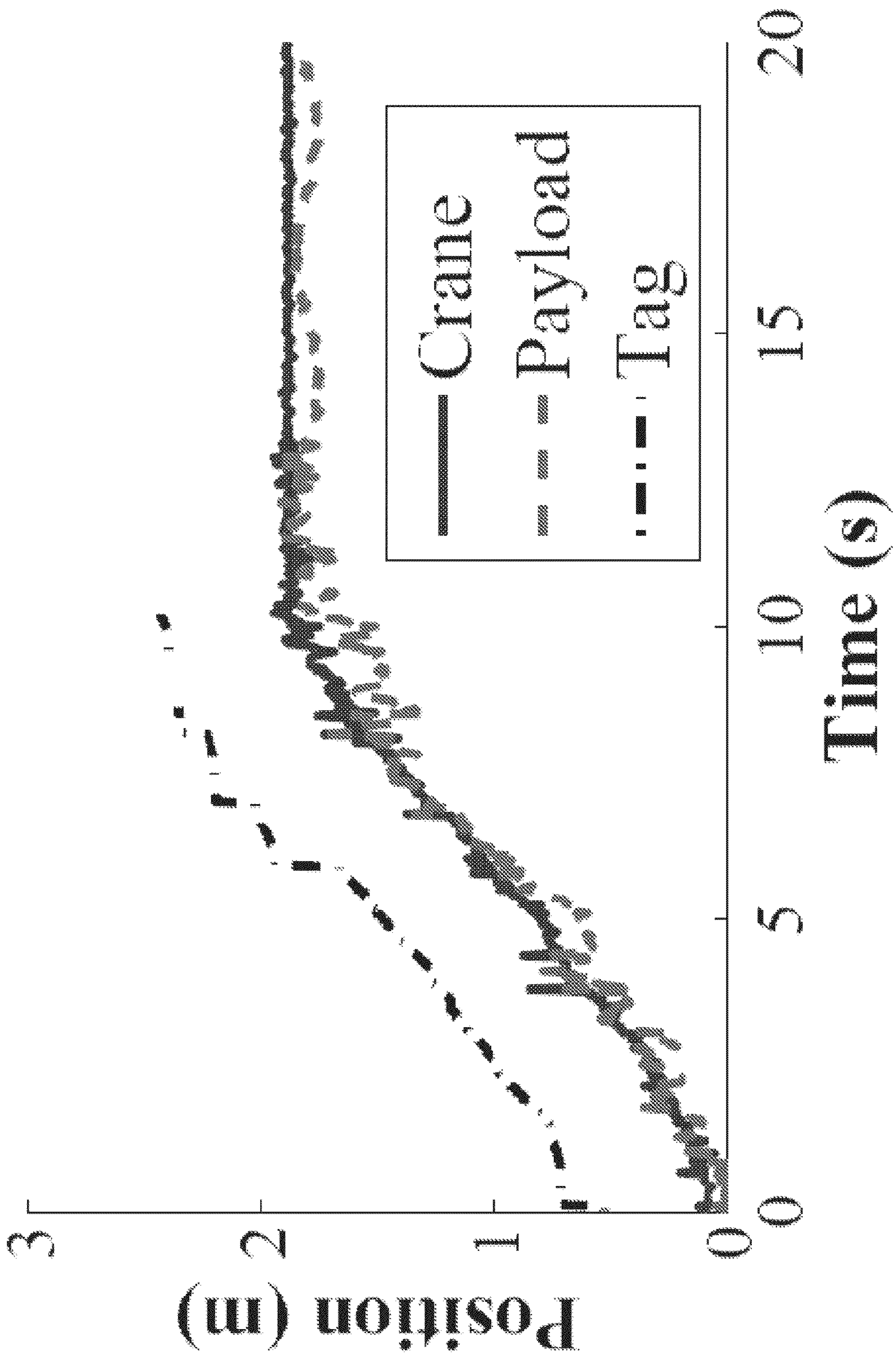


Figure 8

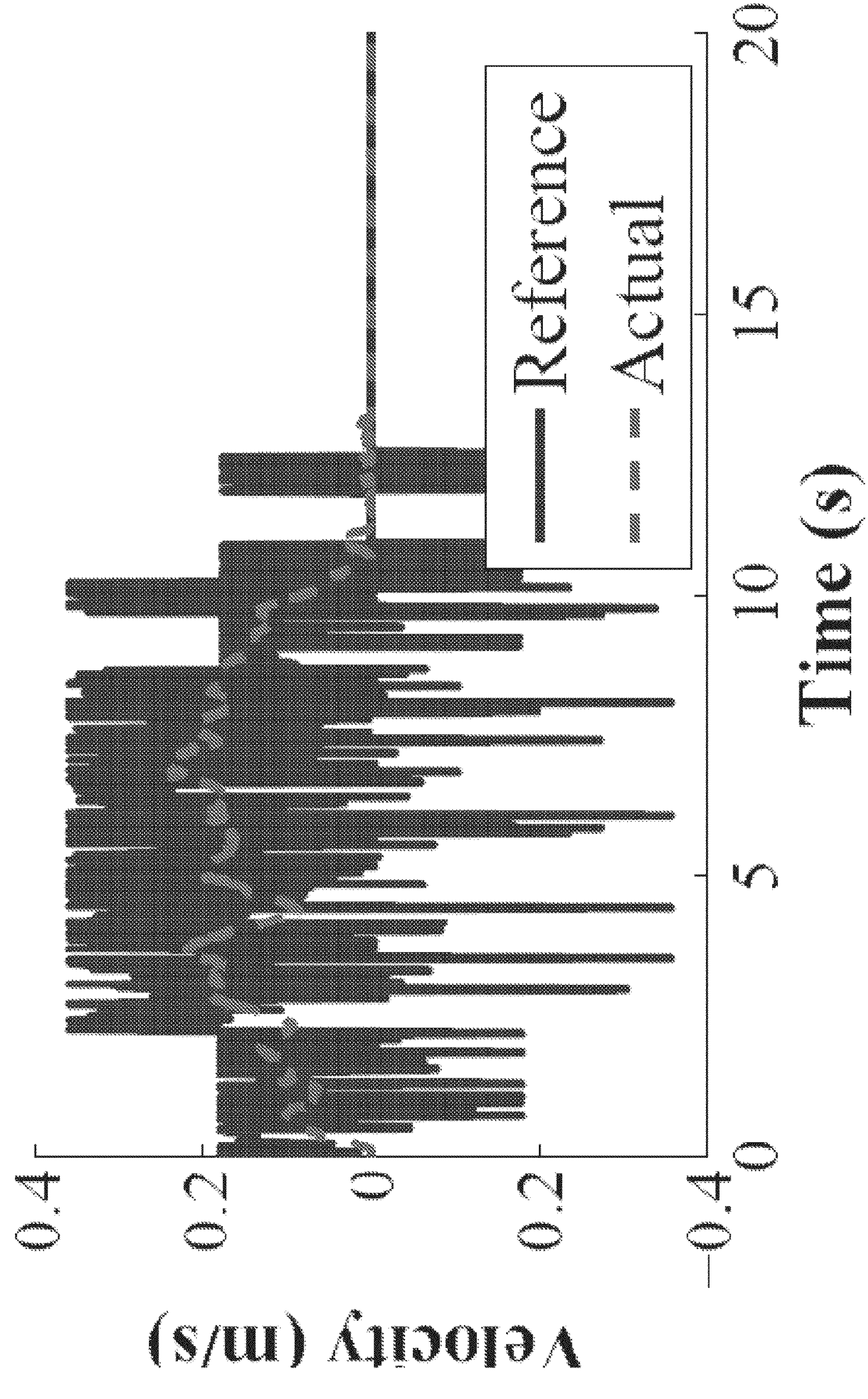


Figure 9

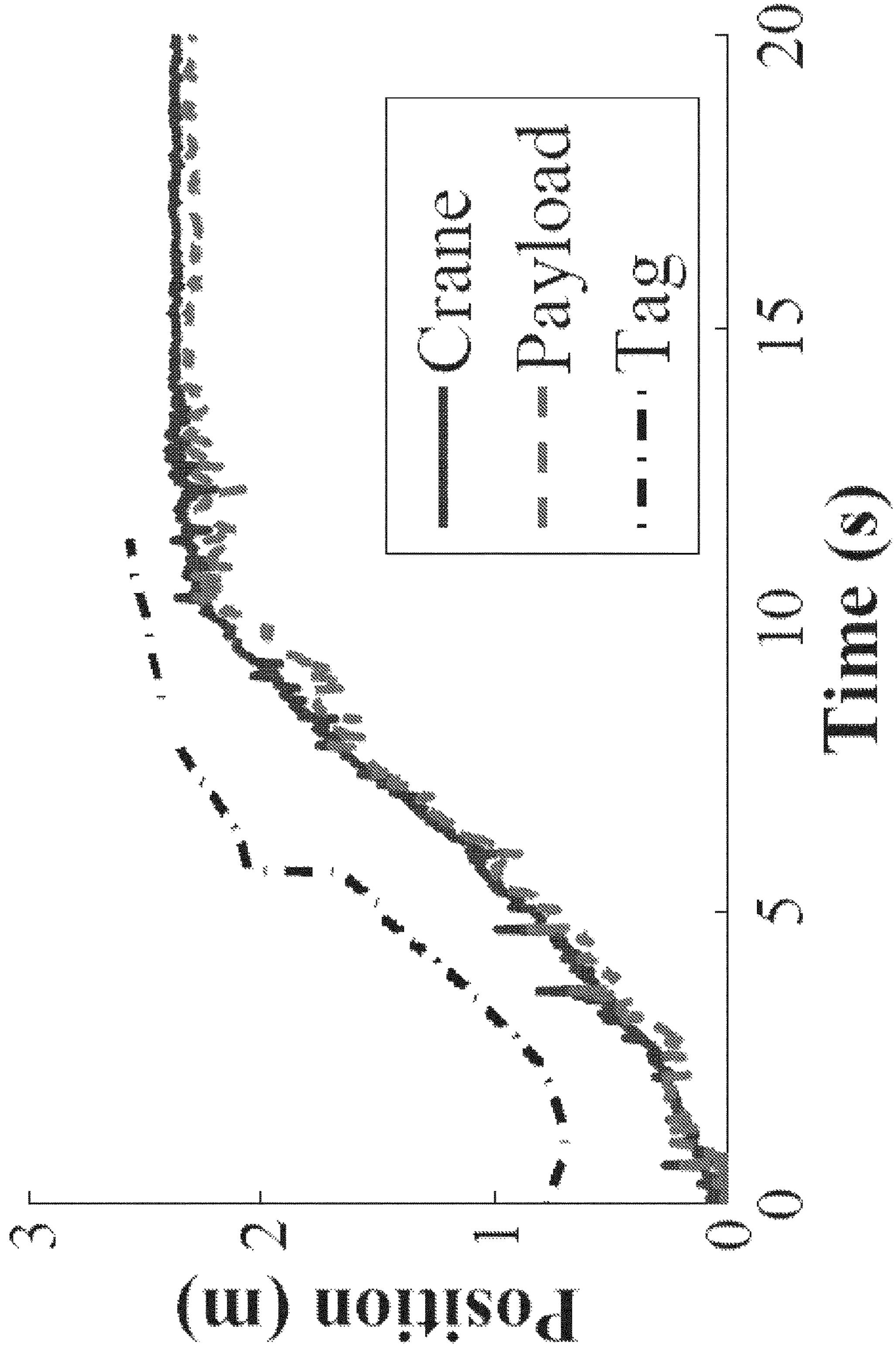


Figure 10

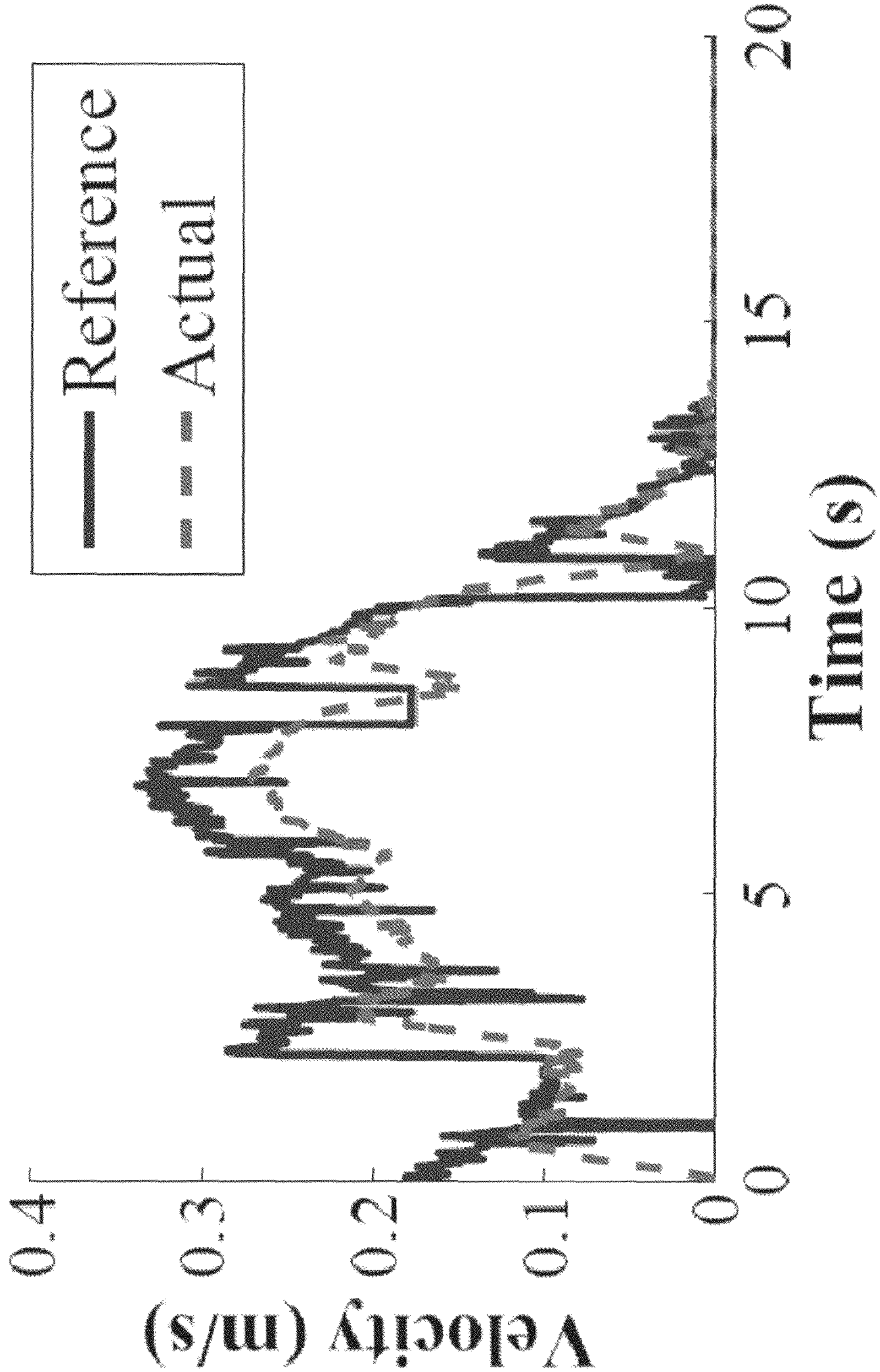


Figure 11

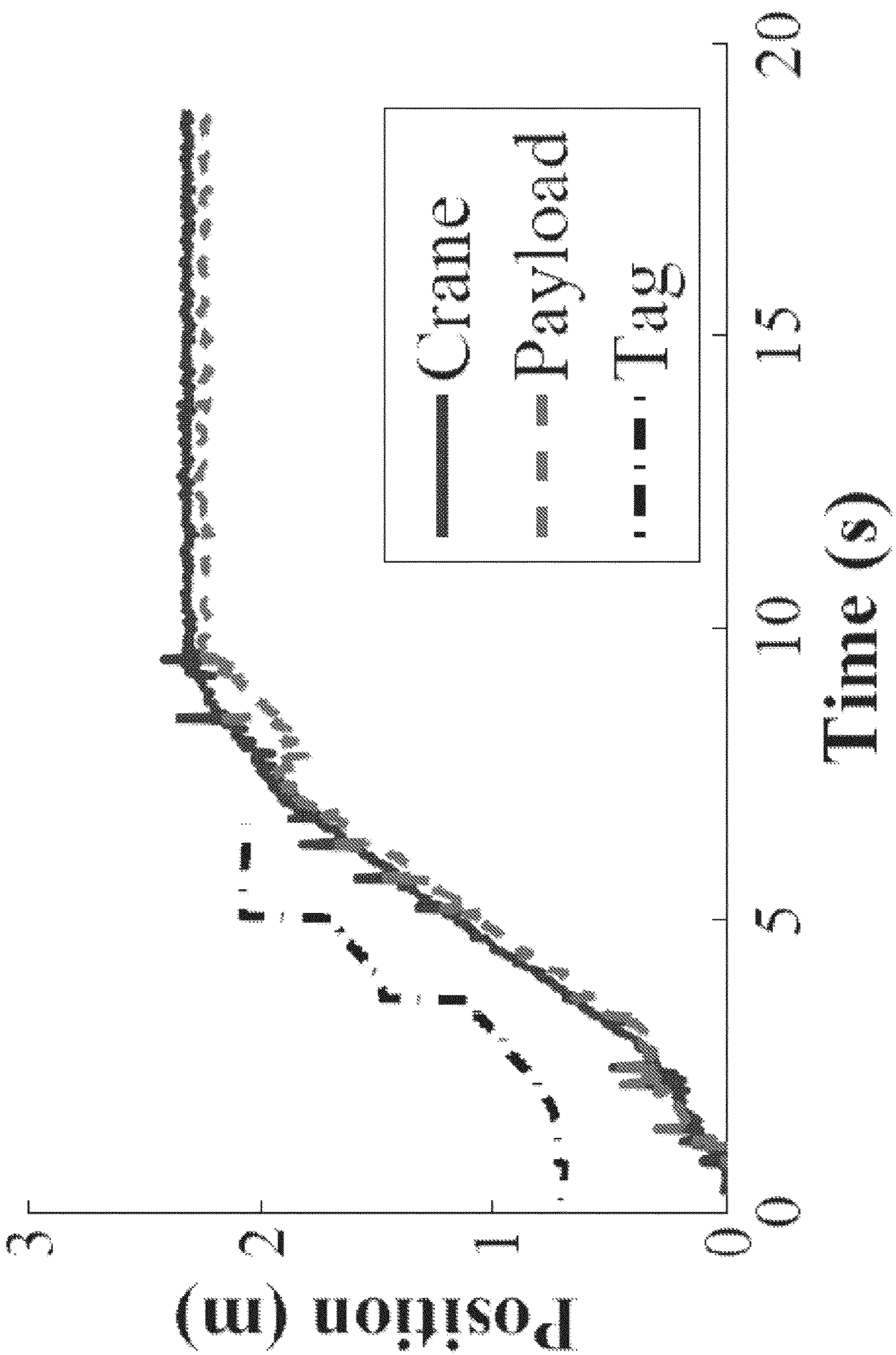


Figure 12

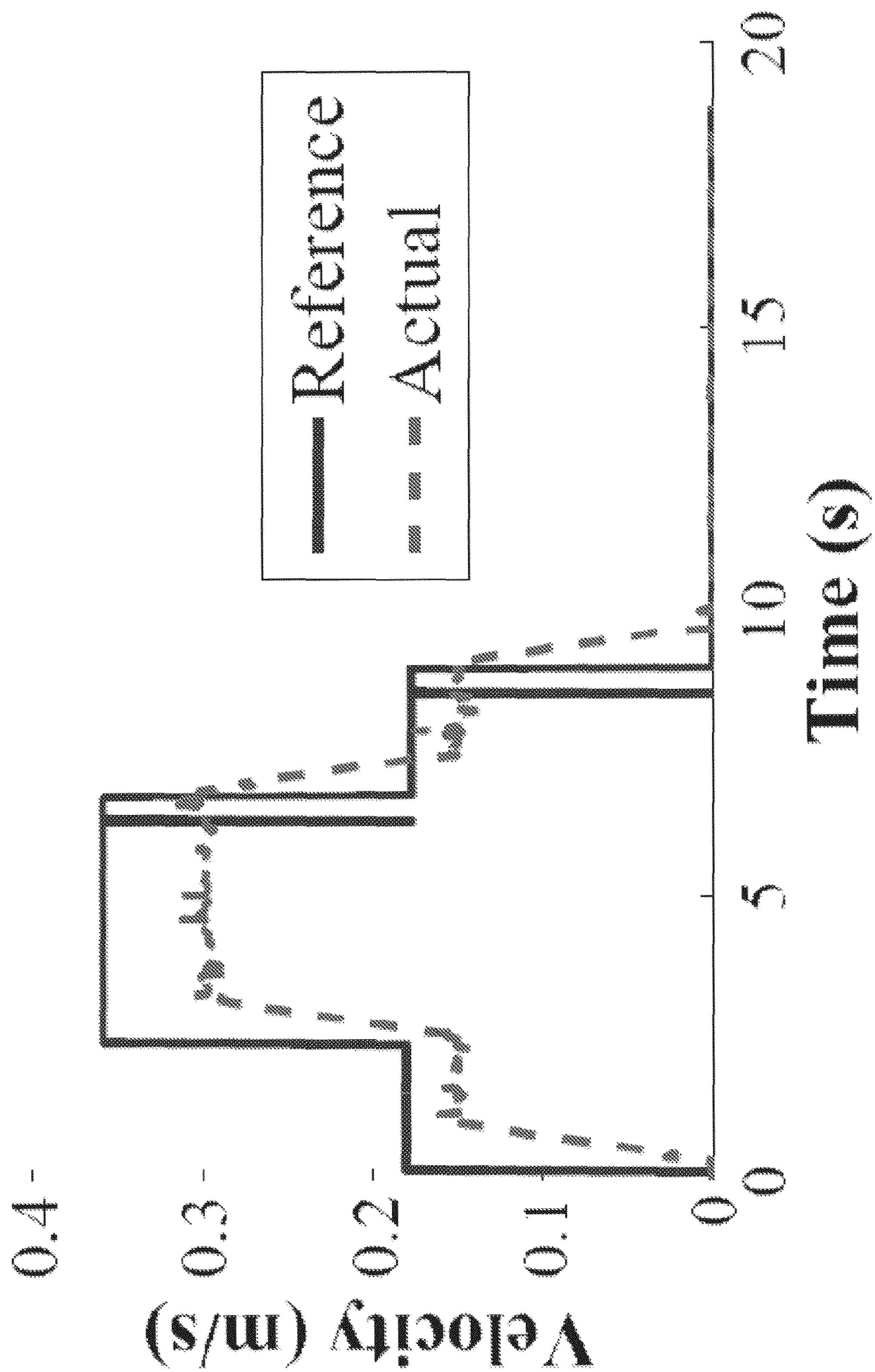


Figure 13

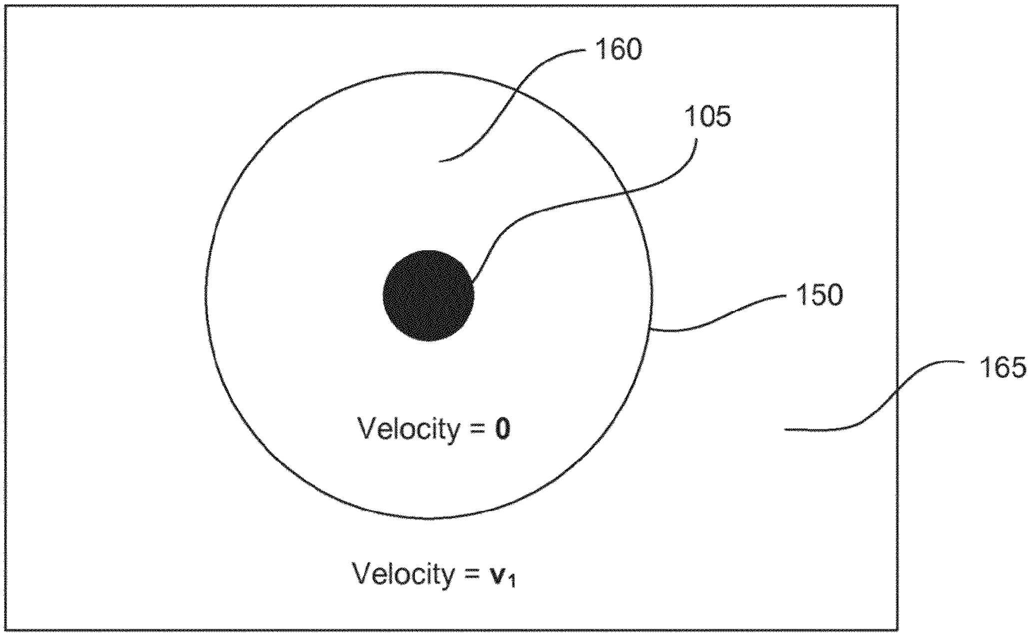


Figure 14A

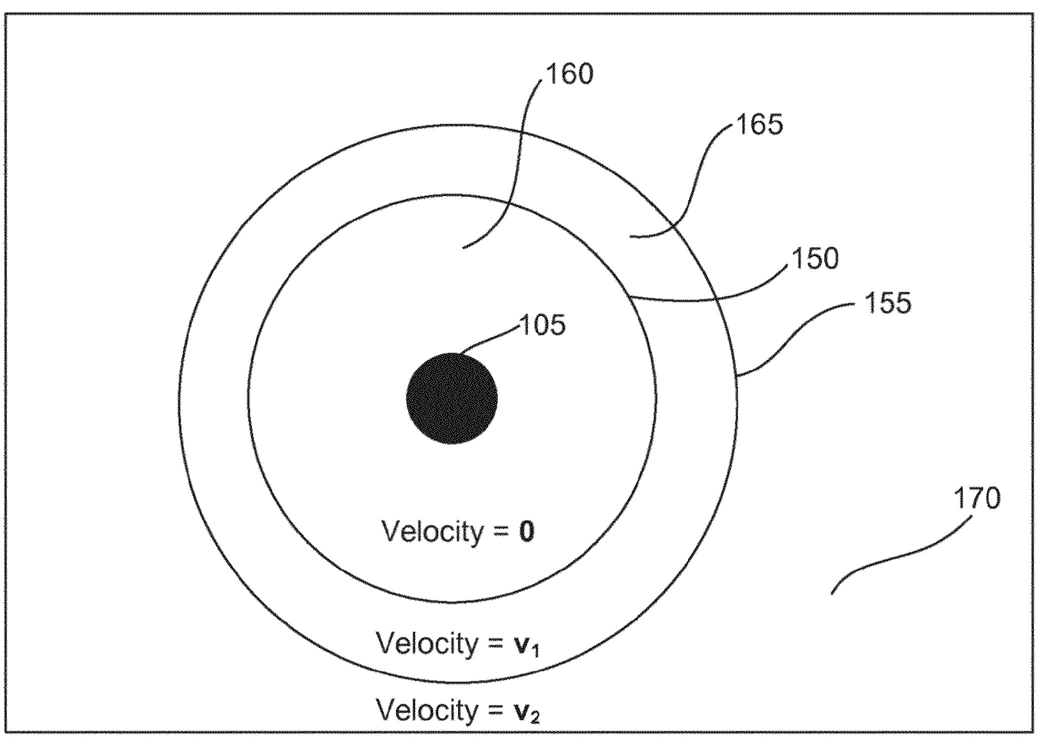


Figure 14B

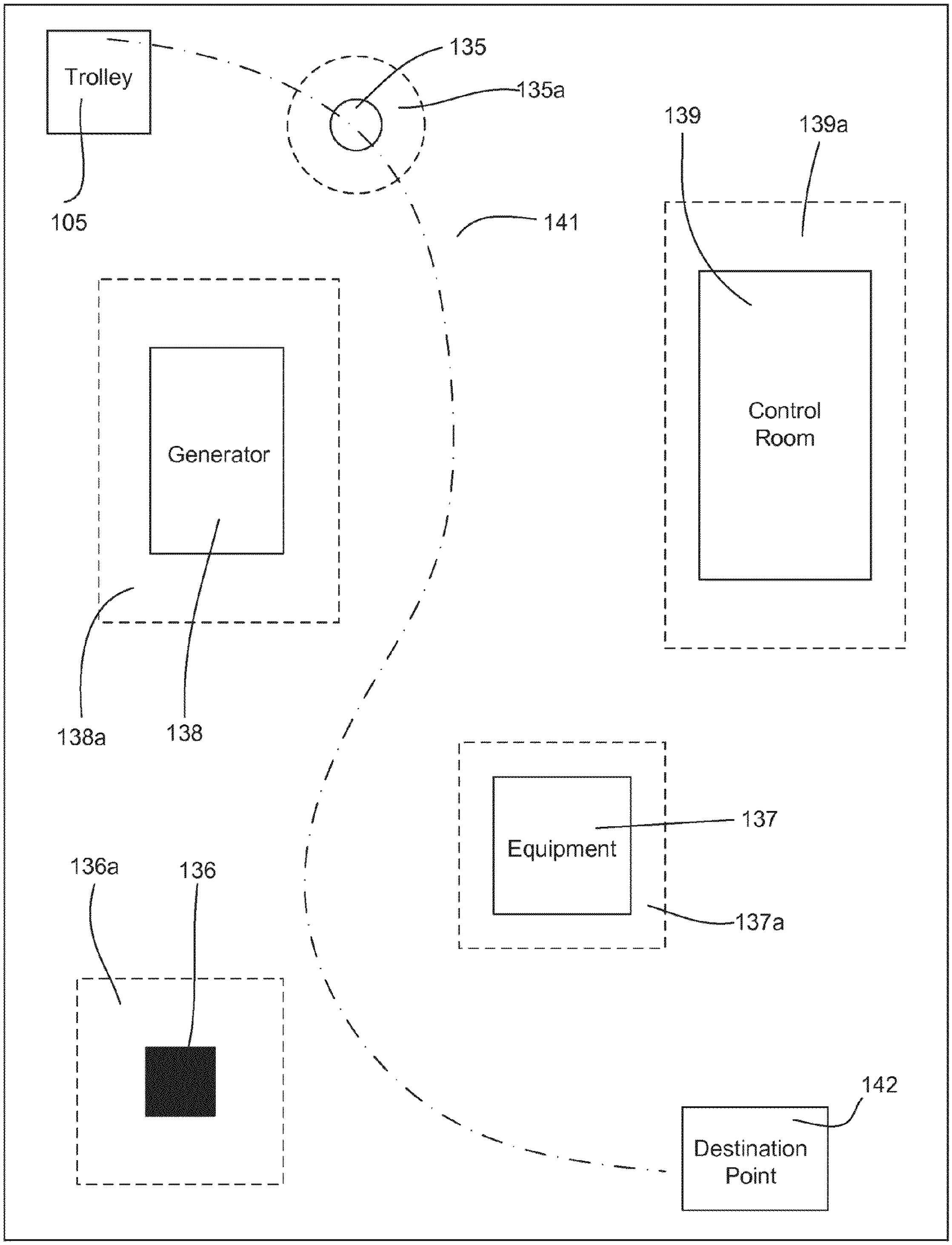

Trolley
105
135
135a
139
139a
141
Generator
Control
Room
138a
138
Equipment
137
136a
136
137a
142
Destination
Point

Figure 15

CRANE CONTROL SYSTEMS AND METHODS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a 35 U.S.C. §371 United States National Stage Application of International Application No. PCT/US2011/33769, filed 25 Apr. 2011, which claims the benefit of U.S. Provisional Application Ser. No. 61/327,337, filed 23 Apr. 2010, and U.S. Provisional Application Ser. No. 61/358,164, filed 24 Jun. 2010, all of which are incorporated herein by reference in their entireties as if fully set forth below.

TECHNICAL FIELD OF THE INVENTION

The various embodiments of the present disclosure relate generally to control systems and methods. More particularly, the various embodiments of the present invention are directed to crane control systems and methods.

BACKGROUND OF THE INVENTION

Cranes play a key role in maintaining the economic vitality of modern-day industry. Their importance can be seen at shipyards, construction sites, warehouses, and in a wide variety of material-handling applications. The effectiveness of crane manipulation is an important contributor to industrial productivity, low production costs, and worker safety. Unfortunately, one inherent property of conventional crane assemblies that is detrimental to efficient operation is the natural tendency for the payload to oscillate like a pendulum, a double-pendulum, or with hoist-related oscillatory dynamics. Because crane operators can only drive the overhead crane trolley—not the payload—there is a response delay from the time the trolley moves to the time the payload moves. This delay results in oscillations in the payload as the trolley slows down (suddenly) or stops moving. The oscillating payload can be very dangerous to the payload, as it may collide with surroundings, or workers in the area. In conventional crane control systems, this delay causes cranes that contain rotational joints an especially challenging control problem because their nonlinear dynamics create additional complexities.

Significant efforts have been made to develop crane control systems that reduce the oscillatory response from both issued commands and external disturbances. Researchers have explored crane problems using neural networks and optimal control. There have also been developments in varying degrees of crane automation. Unfortunately, in addition to facing the challenges of controlling large amplitude, lightly-damped payload swing, operators of conventional crane control systems must also master non-intuitive machine interfaces, which require extensive training. Therefore, expert crane operators typically require years of experience and training. Some examples of conventional non-intuitive crane interfaces include push-button pendants, joysticks, and control levers.

FIG. **1** illustrates a conventional crane control system using a push button pendent interface. The operator must be adept in the cognitive process of transferring the desired manipulation path into a sequence of button presses that will produce the desired motion of the crane trolley **105**. For example, if the operator wants to drive the payload **115** through a cluttered workspace using a push-button pendent **120**, then the desired path must be mapped into a sequence of events where the "Forward", "Backward", "Left", and "Right" buttons are pushed for the correct time duration and in the correct sequence. Furthermore, as operators move through the workspace to drive the payload **115** and monitor its progress, they may rotate their bodies and change the directions they are facing. In such cases, the orientation of the buttons changes as the operators rotate their bodies. For example, the "Forward" button can cause relative motion to the left, right, or even backward. As an additional challenge, the operator can only directly drive the crane trolley **105**, not the payload **115**. Therefore, the operator must account for the time lag between the commanded motion of the crane trolley **105**, which can be many meters overhead, and the delayed oscillatory response of the payload **115**.

While significant strides have been made to improve the operational efficiency of cranes by controlling the dynamic response to issued commands, relatively little consideration has been given to the way in which operators issue those commands. Thus, there is a desire for crane control systems that allow an operator to intuitively issue control commands to a crane that result in minimal payload oscillations, such that the directional crane movement commands are unaffected by the operators changing rotational orientation.

BRIEF SUMMARY OF THE INVENTION

The present invention relates to crane control systems and methods. In a crane system comprising a crane trolley and a supporting device for carrying a payload, an exemplary embodiment of the present invention provides a crane control system useful for simplifying the crane system operation and for maintaining a safe distance between the payload and a specific location (most typically the location of a locator device, which is in the hand of the operator), the locator device for manipulating at least one of the position and speed of the supporting device. The crane control system is also useful in dampening payload oscillations when the crane trolley is either accelerated or decelerated. An exemplary crane control system comprises a real-time position-location module, an on-off controller module, and an input shaper module. The real-time position-location module generates a position signal indicative of a vector between an element of the crane system and the locator device used to manipulate at least one of the position and speed of the crane trolley. In an exemplary embodiment, the element of the crane system is the crane trolley, and the position signal is indicative of the horizontal planar distance between the crane trolley and the locator device. In another exemplary embodiment, the locator device is portable. The on-off controller module maps the position signal to a velocity command signal, wherein the velocity command signal comprises instructions for the crane trolley to move the supporting device in a vector relative to the locator device in at least a first velocity only if the magnitude of the vector between the element of the crane system and the locator device is greater than a cut-off threshold, wherein the at least a first velocity is a substantially constant velocity. The input shaper module manipulates the velocity command signal mapped by the on-off controller module to dampen payload oscillations when the crane trolley is accelerated or decelerated.

In another exemplary embodiment of the present invention, the cut-off threshold is determined as a function of acceleration and/or deceleration properties of the crane trolley. In yet a further exemplary embodiment of the present invention, the cut-off threshold is determined as a function of parameters of the payload. In yet another exemplary embodiment of the present invention, the cut-off threshold is determined in conjunction with properties of the input shaper module. In still yet another exemplary embodiment of the present invention, the cut-off threshold is determined as a function of a vector position of the locator device with respect to the crane trolley.

In another exemplary embodiment of the present invention, the at least a first velocity is equal to the first velocity if the magnitude of the vector between the element of the crane system and the locator device is greater than the cut-off threshold and less than or equal to an intermediate threshold, and the at least a first velocity is equal to a second velocity greater than the first velocity if the magnitude of the vector between the element of the crane system and the locator device is greater than the intermediate threshold.

In yet another exemplary embodiment of the present invention, the real-time position-location module uses characteristics of Ultra-Wide-Band ("UWB") Radio-Frequency ("RF") signals that are emitted by the locator device and received by a plurality of sensors.

Another exemplary embodiment of the present invention provides a radio-frequency-based crane control system comprising a real-time position-location subsystem, an on-off controller module, and an input shaper module. The real-time position location subsystem comprises a portable locator device, a plurality of sensors, and a real-time position-location module. The portable locator device emits UWB RF signals in response to an input. The plurality of sensors receives the UWB RF signals. The real-time position-location module uses the received UWB RF signals to generate a position signal indicative of a horizontal planar distance between the crane trolley and the portable locator device. The on-off controller module maps the position signal to a velocity command signal, wherein the velocity command signal comprises instructions for the crane trolley to move in a vector relative to the locator device in at least a first velocity only if the horizontal planar distance between the crane trolley and the locator device is greater than a cut-off threshold, wherein the at least a first velocity is a substantially constant velocity. The input shaper module manipulates the velocity command signal mapped by the on-off controller module to dampen payload oscillations when the crane trolley is accelerated or decelerated.

In an exemplary embodiment of the crane control system, the at least a first velocity is equal to the first velocity if the horizontal planar distance between the crane trolley and the locator device is greater than the cut-off threshold and less than or equal to an intermediate threshold, and the at least a first velocity is equal to a second velocity greater than the first velocity if the horizontal planar distance between the crane trolley and the locator device is greater than the intermediate threshold.

Another exemplary embodiment of the present invention provides a method of controlling a crane system comprising generating a position signal indicative of a vector between a locator device and an element of the crane system, mapping the position signal to a velocity command signal, and manipulating the velocity command signal to dampen payload oscillations when the crane trolley is accelerated or decelerated. In an exemplary embodiment of the method of controlling a crane system, the step of generating a position signal uses characteristics of UWB RF signals that are emitted by the locator device and received by a plurality of sensors.

These and other aspects of the present invention are described in the Detailed Description below and the accompanying figures. Other aspects and features of embodiments of the present invention will become apparent to those of ordinary skill in the art, upon reviewing the following description of specific, exemplary embodiments of the present invention in concert with the figures. While features of the present invention may be discussed relative to certain embodiments and figures, all embodiments of the present invention can include one or more of the features discussed herein. While one or more embodiments may be discussed as having certain advantageous features, one or more of such features may also be used with the various embodiments of the invention discussed herein. In similar fashion, while exemplary embodiments may be discussed below as system or method embodiments, it is to be understood that such exemplary embodiments can be implemented in various devices, systems, and methods of the present invention.

BRIEF DESCRIPTION OF DRAWINGS

The following Detailed Description of preferred embodiments is better understood when read in conjunction with the appended drawings. For the purposes of illustration, there is shown in the drawings exemplary embodiments, but the subject matter is not limited to the specific elements and instrumentalities disclosed.

FIG. **1** provides a conventional pendent crane control system.

FIG. **2** provides a crane system controlled by an exemplary crane control system of the present invention.

FIG. **3** provides a block diagram of a method of controlling a crane system in accordance with an exemplary embodiment of the present invention.

FIG. **4** provides a block diagram for a pendent crane control system.

FIG. **5** provides a block diagram for a PD feedback crane control system.

FIG. **6** provides a control block diagram for an exemplary crane control system of the present invention.

FIG. **7** provides a graphical illustration of the position of a crane and payload with respect to elapsed time during two meter and three meter point-to-point movements using a pendent crane control system.

FIG. **8** provides a graphical illustration of the position of a crane, payload, and tag with respect to elapsed time during a two meter point-to-point movement using a PD crane control system.

FIG. **9** illustrates the velocity-to-time command signal and the actual velocity-to-time response during a two meter point-to-point movement with a PD crane control system.

FIG. **10** provides a graphical illustration of the position of a crane, payload, and tag with respect to elapsed time during a two meter point-to-point movement using a P crane control system.

FIG. **11** illustrates the velocity-to-time command signal and the actual crane velocity-to-time response during a two meter point-to-point movement with a PD crane control system.

FIG. **12** provides a graphical illustration of the position of a crane, payload, and tag with respect to elapsed time during a two meter point-to-point movement using a crane control system in accordance with an exemplary embodiment of the present invention.

FIG. **13** illustrates the velocity-to-time command signal and the actual crane velocity with respect to time during a two meter point-to-point movement using a crane control system in accordance with an exemplary embodiment of the present invention.

FIG. **14**A illustrates crane trolley velocity when the velocity command signal is mapped in accordance with an exemplary embodiment of the present invention.

FIG. **14**B illustrates crane trolley velocity when the velocity command signal is mapped in accordance with another exemplary embodiment of the present invention.

FIG. **15** illustrates operation of an crane control system in a power generation plant in accordance with an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

To facilitate an understanding of the principles and features of the present invention, various illustrative embodiments are explained below. In particular, the invention is described in the context of being crane control systems and methods. Embodiments of the present invention may be applied to systems or methods for controlling the movement of elements of a crane system via a locator device. Embodiments of the invention, however, are not limited to only use in systems and methods for controlling a crane system. As those of ordinary skill in the art would understand, embodiments of the invention can be used by other systems or methods for controlling other systems via a locator device using, for example, RF signals, SONAR, RADAR, GPS, and the like.

The components described hereinafter as making up various elements of the invention are intended to be illustrative and not restrictive. Many suitable components or steps that would perform the same or similar functions as the components or steps described herein are intended to be embraced within the scope of the invention. Such other components or steps not described herein can include, but are not limited to, for example, similar components or steps that are developed after development of the invention.

Various embodiments of the present invention relate to crane control systems for controlling crane systems. As shown in FIG. **2**, an exemplary crane system comprises a crane trolley **105** and a supporting device **110**. The crane trolley **105** comprises a motor and is configured to move in multiple directions along rails **140** or other support structures. The supporting device **110** is in mechanical communication with the trolley **105** and is used for carrying a payload **115**. The trolley **105** can raise and lower the supporting device **110** using hoist motors. The supporting device **110** can be any supporting structure known in the art or developed at a later time, including, but not limited to, a hook that can attach to a payload. Exemplary embodiments of the present invention provide crane control systems useful for simplifying crane system operation and for maintaining a safe distance between the payload **115** and a desired location, typically a region around a locator device **135**, wherein the locator device **135** can be held by an operator. Thus, the invention provides superior operator safety. Some exemplary embodiments of the present invention provide crane control systems that manipulate at least one of the position and speed of the crane system, or individual components thereof. Additionally, some exemplary embodiments of the present invention also are useful in dampening payload oscillations when the crane trolley **105** is either accelerated or decelerated.

As shown in FIG. **6**, an exemplary embodiment of the present invention provides a crane control system comprising a real-time position-location module **305**, an on-off controller module **310**, and an input-shaper module **315**. The real-time position-location module **305** can generate a position signal indicative of a vector between an element of the crane system and a desired location (most typically a locator device **135**). The vector between the element of the crane system and the desired location or locator device **135** can be indicative of the horizontal planar distance and vertical planar distance between the element of the crane system and the desired location or locator device **135**. The element of the crane system can include, but is not be limited to, the crane trolley **105**, the supporting device **110**, or the payload **115**. The locator device **135** can be many devices that can be used to create a position signal, including, but not limited to, a Radio-Frequency Identification ("RFID") tag, a SONAR device, a RADAR device, a Global Positioning System ("GPS") device, and the like. The locator device **135** can also be portable or stationary. In an exemplary embodiment of the present invention, the locator device **135** is a portable RFID tag that is carried around a workspace by an operator. The real-time position-location module **305** can measure many different distances between the element of the crane system and the locator device **135** (FIG. **2**). In an exemplary embodiment, the position signal is indicative of the horizontal planar distance **130** between the crane trolley **105** and the locator device **135**. The position signal can be used to manipulate at least one of the position and speed of the crane system, or components thereof. In some embodiments of the present invention, the real-time position location module **305** comprises instructions stored in memory and capable of implementation by a computer or controller.

The on-off controller module **310** of the exemplary crane control system can map the position signal to a velocity command signal. The velocity command signal can comprise instructions for the crane trolley **105** to move the supporting device **110** in a vector relative to the locator device **135** in at least a first velocity only if the magnitude of the vector between an element of the crane system and the locator device **135** is greater than a cut-off threshold **150**, wherein the at least a first velocity is substantially constant (FIG. **14**A). Thus, in some embodiments, the crane trolley **105** will not move if the magnitude of the vector between the element of the crane system and the locator device **135** is less than or equal to the cut-off threshold **150**, and will move in at least a substantially constant first velocity if the magnitude of the vector is greater than the cut-off threshold **150**. In some embodiments of the present invention, the at least a first velocity is equal to the first velocity if the magnitude of the vector between the element of the crane system and the locator device **135** is greater than a cut off threshold and less than or equal to an intermediate threshold **155**, and the at least a first velocity is equal to a second velocity greater than the first velocity if the magnitude of the vector between the element of the crane system and the locator device **135** is greater than the intermediate threshold **155** (FIG. **14**B). Thus, in these embodiments, the crane trolley **105** has three discrete velocities. It will not move (velocity equal to zero) if the distance between the element of the crane system and the locator device **135** is less than or equal to the cut-off threshold **150**. The crane trolley **105** will move at a first velocity if the distance is greater than the cut-off threshold **150** but less than or equal to the intermediate threshold **155**. And, the crane trolley **105** will move at a second velocity if the distance is greater than the intermediate threshold **155**. In these embodiments, if the second velocity is greater than the first velocity, the crane trolley **105** will move at a slower velocity when it is closer to the locator device **135** and a faster velocity when it is further away from the locator device **135**. In some embodiments of the present invention, the on-off controller module **310** comprises instructions stored in memory and capable of implementation by a computer or controller.

The scope of the invention is not limited to a cut-off threshold **150** and an intermediate threshold **155** corresponding to a first velocity and a second velocity. Instead, the present invention can employ many different thresholds corresponding to many different velocities depending on the desired application. Additionally, some embodiments of the present invention may include a plurality of locator devices defining a plurality of desired locations of safety. For example, as shown in FIG. **15**, the present invention may be applied to a crane system in a power generation plant. The power generation plant may have a control room **139**, generator **138**, concrete or steel columns **136**, and other equipment **137**, which may be damaged if struck by the payload **115**. Similarly, the payload **115** may be damaged if it strikes the various components. An exemplary crane control system of the present invention allows an operator to move a payload **115** suspended from a crane trolley **105** around the power plant to a destination point **142** while avoiding from striking any of the components. To move the payload **115** to the destination point **142**, the operator need only walk throughout the workspace in the path **141** the operator wishes the payload **115** to travel, and the payload **115** will follow the locator device **135** carried by the operator. A cut-off threshold defines a desired location of safety **135***a* around the locator device **135**, such that the payload will not strike the operator. Each component **136**, **137**, **138**, and **139** can also have a desired safety zone **136***a*, **137***a*, **138***a*, and **139***a* in which the payload will not enter. If the operator attempts to move payload **115** into any of the safety zones **136***a*, **137***a*, **138***a*, and **139***a*, the trolley **105** will stop moving. Each safety zone **136***a*, **137***a*, **138***a*, and **139***a* may be stored into a memory within the crane control system. Alternatively, safety zones **136***a*, **137***a*, **138***a*, and **139***a* can be defined by additional locator devices placed about each component **136**, **137**, **138**, and **139**, such that if the distance from the payload **115** to one of the locator devices on a component is less than a cut-off threshold for that particular locator device, the trolley **105** will stop moving. As an additional safety feature, workers around the workspace may each carry locator devices, such that if the distance between the payload **115** and the locator device carried by a worker is less than a cut-off threshold, the trolley **105** will stop moving, thus ensuring workers are not struck by the payload **115**. When multiple locator devices are used, the locator device **135** carried by the operator is used to control the direction of the trolley's **105** movement. Additionally, because some embodiments of the present invention uses multiple thresholds, e.g. a cut-off threshold and an intermediate threshold, the trolley **105** will move faster when it is further away from the operator or safety zones **136***a*, **137***a*, **138***a*, and **139***a* (greater than an intermediate threshold), and the trolley **105** will move slower when it is closer to the operator or safety zones **136***a*, **137***a*, **138***a*, and **139***a* (greater than a cut-off threshold and less than an intermediate threshold).

The various embodiments of the present invention are not limited in moving the payload or supporting device **110** in a horizontal sense, but instead, some embodiments of the present invention allow an operator to control the vertical movement of the supporting device **110**, and thus the payload **115**. Thus, in some embodiments of the present invention, the velocity command signal can comprise instructions for the crane trolley to move an element of the crane system, most typically the supporting device **110**, in a vector—horizontal, vertical, or a combination thereof—relative to the locator device **135**. In some embodiments of the present invention, the velocity command signal can comprise instructions for the crane trolley to raise and lower the supporting device **110**, and thus the payload **115**, in a vertical direction.

In an exemplary embodiment of the present invention, the position signal is indicative of the vector between an element of the crane system and the desired location of safety, most typically the locator device **135**. Thus, if the locator device **135** is raised or lowered by the operator, such that the magnitude of the vertical component of the vector is greater than a cut-off threshold, the velocity command signal will comprise instructions for the crane trolley **105** to raise or lower the supporting device **110** in a vector relative to the locator device **135**. In another exemplary embodiment of the present invention, the locator device **135** comprises operator input elements, such that an operator input may be used to control the vertical movement of the supporting device **110**. As those skilled in the art would recognize, the operator input elements may be many operator input elements known in the art or developed at a later time, including, but not limited to, buttons, switches, joysticks, levers, and the like.

In some embodiments of the present invention, an operator may make "gesture-like" movements with the locator device **135**, such that the position, velocity, or acceleration of the locator serve as the basis to raise and lower the supporting device **110**. For example, and not limitation, to raise the supporting device **110**, the operator could: move the locator device **135** from a lower position to a higher position—a position-based gesture; move the locator device **135** at a constant speed upwards—a velocity-based gesture; or accelerate quickly, or "flick," the locator **135** device upwards—an acceleration-based gesture.

The input shaper module **315** can manipulate the velocity command signal mapped by the on-off controller module **310** to dampen payload oscillations or supporting device oscillations when the crane trolley **105** is accelerated or decelerated. In some embodiments of the present invention, the input shaper module **315** comprises instructions stored in memory and capable of implementation by a computer or controller. In some embodiments of the present invention, the input shaper module **315** manipulates the velocity command signal by convolving a baseline input command with a series of impulses at specific time intervals, thus resulting in a shaped command that will reduce residual vibration. In order to determine the impulses amplitudes and time locations for the input shaper module **315**, some embodiments of the present invention satisfy certain design constraints. One such design constraint can be a limit on the amplitude of vibration caused by the input shaper module **315**. In some embodiments, the Normalized Residual Vibration ("NRV") amplitude of an under-damped, second-order system from a sequence of n impulses is represented by Equation 1:

$$\mathrm{NRV}=V(\omega,\zeta)=e^{-\zeta\omega t_n}\sqrt{[C(\omega,\zeta)]^2+[C(\omega,\zeta)]^2} \qquad \text{Equation 1:}$$

where $C(\omega, \zeta)$ can be defined by Equation 2, and $S(\omega,\zeta)$ can be defined by Equation 3:

$$C(\omega, \zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i} \cos\left(\omega t_i \sqrt{1-\zeta^2}\right) \qquad \text{Equation 2}$$

$$S(\omega, \zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i} \sin\left(\omega t_i \sqrt{1-\zeta^2}\right) \qquad \text{Equation 3}$$

where ω is the natural frequency of the crane system, ζ is the damping ratio, and A_i and t_i are the i^{th}-impulse amplitude and time, respectively. Equation 1 can give the ratio of vibration with input shaping to that without input shaping.

In some embodiments of the present invention, a constraint on residual vibration amplitude can be formed by setting Equation 1 less than or equal to a tolerable level of residual vibration at the modeled natural frequency and damping ratio. In an exemplary embodiment of the present invention, the input shaping module **315** is a Zero Vibration ("ZV") input shaping module, such that the tolerable amount of vibration is set to zero. This can result in the shaper illustrated in Equation 4:

$$ZV = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & \frac{\pi}{\omega\sqrt{1-\zeta^2}} \end{bmatrix} \quad \text{Equation 4}$$

where K is represented by Equation 5.

$$K = e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}} \quad \text{Equation 5}$$

In some embodiments of the present invention, a crane control system comprises a real-time position-location subsystem. In some embodiments of the present invention, the real-time position-location subsystem comprises a locator device **135**. The locator device **135** can be a portable locator device. In some embodiments, the locator device is configured to emit RF signals. In some embodiments, the locator device is configured to emit UWB RF signals. In some embodiments, the RF signals are emitted in response to an input, such as pushing a button, actuating a switch, receiving an input control system, and the like. The real-time position-location subsystem can also comprise a plurality of sensors **125**. The plurality of sensors **125** can be placed around the perimeter of a workspace. In some embodiments of the present invention, the perimeter of the workspace can be defined by all possible locations in which the crane trolley **105** can travel. The plurality of sensors **125** can receive the signals emitted by the locator device **135**. The real-time position location subsystem can comprise a real-time position-location module **305**. The real-time position-location module **305** can calculate the three dimensional location of the locator device **135**. In some embodiments, the real-time position-location module **305** calculates the three dimensional location of the locator device **135** using the time difference and angle of arrival of the RF signals at the plurality of sensors **125**. The real-time position-location module **305** can then use the position of the locator device **135** relative to an element of the crane system to generate a position signal.

The cut-off threshold **150** and/or intermediate threshold **155** can be determined numerous ways in various embodiments of the present invention. In an exemplary embodiment of the present invention, the cut-off threshold **150** and/or the intermediate threshold **155** is determined as a function of the acceleration and/or deceleration properties of the crane trolley **105**. Thus, in some embodiments, if the crane trolley **105** decelerates slowly, the cut-off threshold **150** can be increased to ensure that the payload **115** or supporting device **110** does not strike the locator device **135**, or operator thereof. In another exemplary embodiment of the present invention, the cut-off threshold **150** and/or the intermediate threshold **155** can be determined as a function of parameters of the payload **115**, including, but not limited to, the weight, length, width, height, geometrical shape, and material of the payload **115**. For example, in some embodiments of the present invention, if the payload **115** extends one meter outward in a direction from the supporting device **110**, then the cut-off threshold **150** may be set to greater than one meter in that direction to ensure the payload **115** does not strike the locator device **135**, or operator thereof. An yet another exemplary embodiment of the present invention, the cut-off and/or intermediate threshold **155** can be determined in conjunction with properties of the input shaper module **315**. Thus, for example, in some embodiments of the present invention, if the input shaper module **315** is more aggressive or longer, the cut-off threshold **150** may be higher to give the crane trolley **105** adequate time to stop, thus ensuring that the payload **115** or supporting device **110** does not strike the locator device **135**, or operator thereof. In still yet another exemplary embodiment of the present invention, the cut-off threshold **150** and/or intermediate threshold **155** can be determined as a function of a vector position—horizontal, vertical, or a combination thereof—of the locator device **135** with respect to the crane trolley **105**. Thus, in some embodiments of the present invention, the cut-off threshold **150** can be different values for different directions relative to the locator device **135**, i.e. a geometrically-shaped, such as a rectangular-shaped or square-shaped, cut-off zone may be created by changing the cut-off threshold **150** depending on the direction of the locator device **135** relative to an element of the crane system.

FIG. **2** provides an exemplary crane system adapted to be controlled by an exemplary embodiment of the present invention. The crane system comprises a crane trolley **105** and supporting device **110** suspended from the trolley in a pendulum-like matter and carrying a payload **115**. An exemplary crane control system uses a real-time position location module **305** to generate a position signal indicative of the horizontal planar distance **130** between the locator device **135**, which is an RFID tag, and the crane trolley **105**. The locator device **135** emits RF signals that are received by a plurality of sensors **125** located about a perimeter of a workspace. An on-off controller module **310** maps the position signal to a velocity command signal. If the horizontal planar distance **130** is less than or equal to a cut-off threshold **150**, the velocity command comprises instructions for the crane trolley **105** to exhibit a zero velocity. If the horizontal planar distance **130** is greater than a cut-off threshold **150**, then the velocity command comprises instructions for the crane trolley **105** to move in a vector relative to the locator device **135** in at least a first velocity. The crane trolley **105** can continue to move in at least a first velocity so long as the horizontal planar distance **130** is greater than the cut-off threshold **150**. Thus, an operator may hold the locator device **135** and move it around the workspace, and the payload **115** will follow the locator device **135** so long as the horizontal planar distance **130** is greater than the cut-off threshold **150**.

In addition to crane control systems, the present invention provides methods of controlling a crane system. FIG. **3** provides a block diagram of a method of controlling a crane system **200** in accordance with an exemplary embodiment of the present invention. An exemplary method of controlling a crane system **200** comprises generating a position signal indicative of a vector between a desired location, most typically a locator device **135**, and an element of the crane system **205**, mapping the position signal to a velocity command signal **210**, and manipulating the velocity command signal to dampen payload oscillations when the crane trolley **105** is accelerated or decelerated **215**. The velocity command signal can comprise instructions for the crane trolley **105** to move the supporting device **110** in a vector relative to the locator device **135** in at least a first velocity only if the magnitude of the vector between the element of the crane system and the locator device **135** is greater than a cut-off threshold **150**.

Embodiments of the present invention provide many improvements over pendent, Proportional Derivative ("PD") feedback, and Proportional ("P") feedback crane control systems. A block diagram for a pendent crane control system is illustrated in FIG. **4**. In this system, a crane operator is required to analyze the workspace, consider the required manipulation goal, and then decide on a course of action. This plan is then implemented by pushing buttons on the control pendent. These buttons energize the motors to move the overhead crane at constant velocity. When a button is released, the crane will stop. Due to the pendulum-like nature of the payload, this type of movement will, in general, induce significant residual oscillations. FIG. **7** provides a graphical illustration of the position of a crane and payload with respect to elapsed time during two meter and three meter point-to-point movements using the pendent crane control system. It is clear that the oscillatory position of the payload is extreme, and could be very dangerous to both the payload and anyone or anything in proximity to the payload.

A block diagram for a PD feedback crane control system is illustrated in FIG. **5**. The position of an RFID tag is compared to the position of the crane trolley to generate an error signal, e. This position error signal is first mapped into a non-constant velocity command signal as shown in Equation 6.

$$\text{Command} = \begin{cases} 0\%: \; e \le e_{min} \\ 100\% \times \dfrac{e - e_{min}}{e_{max} - e_{min}}: \; e_{min} < e < e_{max} \\ 100\%: \; e \ge e_{max} \end{cases} \quad \text{Equation 6}$$

A PD feedback control law is then applied and the result is passed through a saturator to ensure that velocity and acceleration limits are not exceeded. This output is then modified by an input shaper so that the command signal sent to the crane will not excite payload swing.

Although the PD crane control system reduces payload swing, there are several drawbacks to such systems. By choosing an aggressive P gain, the crane is able to closely tack the movement of the tag. Aggressive P gains, however, result in high amplitude payload sway. Conversely, increasing the D gain increases damping to smooth out aggressive commence, but at the cost of sluggish crane movements. Therefore, the inclusion of an input shaper inside the feedback loop is used in an attempt to limit or eliminate residual oscillations, while allowing high P gains such that the crane follows the tag aggressively. The crane itself, however, still responds in an oscillatory manner, which is separate from the oscillating payload. Thus, these conventional systems present an inherent trade-off between following the tag in an aggressive manner and system settling time.

FIG. **8** provides a graphical illustration of the position of a crane, payload, and tag with respect to elapsed time during a two meter point-to-point movement using a PD crane control system. The control system design parameters were chosen by trial and error to produce the most satisfactory performance in terms of rise time and settling time. In the experimental point-to-point movement represented in FIG. **8**, it took the crane and payload approximately ten seconds to reach the desired position. In addition to the lengthy time requirement for the conventional PD crane control system, significant issues with noisy signals arise. Because there is significant signal noise in both the tag and crane positions, as shown in FIG. **8**, the error signal will also be noisy. When PD is applied to the error, the noise is amplified (principally due to the derivative component). Subsequently, the reference velocity command to the motors contains many high frequency spikes, as illustrated by FIG. **9**. Due to the inertia of the crane, however, the crane acts as a low pass filter and is incapable of following the fast-switching reference velocity. Nevertheless, high frequency components are still undesirable because they may excite unmodeled higher modes, such as a trolley rock phenomenon. This phenomenon is responsible for the residual payload oscillations in FIG. **8**.

To attempt to alleviate some of the problems with PD crane control systems, some systems set the derivative component to zero. FIG. **10** provides a graphical illustration of the position of a crane, payload, and tag with respect to elapsed time during a two meter point-to-point movement using this P crane control system. FIG. **11** illustrates the velocity-to-time response during the same two meter point-to-point movement with the P crane control system. While the command signal contains less noise than the PD crane control system, it still takes ten seconds to move two meters. Further, the noise in the reference command signal prevents the crane from making sustained movements at maximum velocity. Thus, in FIGS. **9** and **11**, the crane never reaches a desired maximum velocity.

FIG. **6** provides a control block diagram for an exemplary crane control system of the present invention. The exemplary embodiment does not use the PD or saturator blocks like conventional systems. Instead, the exemplary crane control system comprises an on-off controller module **310**. In an exemplary embodiment of the present invention, the on-off controller module **310** maps a position signal, e, to a velocity command signal as indicated in Equation 7.

$$\text{Command} = \begin{cases} 0: \; e \le e_{cut\text{-}off} \\ v_1: \; e > e_{cut\text{-}off} \end{cases} \quad \text{Equation 7}$$

FIG. **14**A illustrates crane trolley velocity when the velocity command signal is mapped using Equation 7 in accordance with an exemplary embodiment of the present invention. When the locator device **135** is in the cut-off-zone **160**, i.e. the position signal is less than or equal to a cut-off threshold **150**, $e_{cut\text{-}off}$, then the velocity command signal is set to zero, and when the locator device in the v_1-zone **165**, i.e. the position signal is greater than the cut-off threshold **150**, then the velocity command is set to a first velocity, v_1. Additionally, in some embodiments, when the position signal is greater than the cut-off threshold **150**, the velocity command is set to at least a first velocity.

In another exemplary embodiment of the present invention, the on-off controller maps a position signal to a velocity signal as indicated in Equation 8.

$$\text{Command} = \begin{cases} 0: \; e \le e_{cut\text{-}off} \\ v_1: \; e_{cut\text{-}off} < e \le e_{int} \\ v_2 \; e > e_{int} \end{cases} \quad \text{Equation 8}$$

FIG. **14**B illustrates crane trolley velocity when the velocity command signal is mapped using Equation 8 in accordance with an exemplary embodiment of the present invention. When the locator device **135** is in the cut-off-zone **160**, i.e. the position signal is less than or equal to a cut-off threshold **150**, then the velocity command signal is set to zero. When the locator device **135** is in the v_1-zone, i.e. the position signal is greater than the cut-off threshold **150** but less than or equal to an intermediate threshold **155**, e_{int}, then the velocity command signal is set to a first velocity. Finally, when the locator device **135** is in the v_2-zone, i.e. the position signal is greater than the intermediate threshold **155**, then the velocity command signal is set to a second velocity.

FIG. **12** provides a graphical illustration of the position of a crane, payload, and tag with respect to elapsed time during a two meter point-to-point movement using an exemplary crane control system of the present invention. FIG. **13** illustrates the reference velocity command signal and actual velocity with respect to time during the same two meter point-to-point movement with the exemplary crane control system of the present invention. The cut-off threshold **150** was set to 0.3 m. FIG. **12** illustrates that the crane moved two meters is only 7.5 seconds −2.5 seconds faster than with the PD feedback or P feedback crane control systems. Further, it is clear from FIG. **13** that noise is greatly reduced in the reference velocity command signal; thus, the crane is able to reach and sustain movements at its maximum velocity.

The present invention also improves over PD feedback and P feedback crane control systems by requiring less design components. PD feedback and P feedback systems require design of P gains, D gains, e_{min}, e_{max}, an input shaper, and/or filter components. On the other hand, some exemplary embodiments of the present invention do not require design of P gains, D gains, e_{max}, or the filter components; thus, crane control system design is greatly simplified.

It is to be understood that the embodiments and claims disclosed herein are not limited in their application to the details of construction and arrangement of the components set forth in the description and illustrated in the drawings. Rather, the description and the drawings provide examples of the embodiments envisioned. The embodiments and claims disclosed herein are further capable of other embodiments and of being practiced and carried out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purposes of description and should not be regarded as limiting the claims.

Accordingly, those skilled in the art will appreciate that the conception upon which the application and claims are based may be readily utilized as a basis for the design of other structures, methods, and systems for carrying out the several purposes of the embodiments and claims presented in this application. It is important, therefore, that the claims be regarded as including such equivalent constructions.

Furthermore, the purpose of the foregoing Abstract is to enable the International Receiving Office and the public generally, and especially including the practitioners in the art who are not familiar with patent and legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The Abstract is neither intended to define the claims of the application, nor is it intended to be limiting to the scope of the claims in any way. It is intended that the application is defined by the claims appended hereto.

What is claimed is:

1. In a crane system comprising a crane trolley and a supporting device for carrying a payload, an improved crane control system useful for simplifying the crane system operation and in maintaining a safe distance between the payload and a desired location of safety, wherein a locator device is used for manipulating at least one of the position and speed of the supporting device, the crane control system also useful in dampening payload oscillations when the crane trolley is accelerated or decelerated, the improved crane control system comprising:

- a real-time position-location module generating a position signal indicative of a vector between an element of the crane system and the desired location;
- an on-off controller module mapping the position signal to a velocity command signal, wherein the velocity command signal comprises instructions for the crane trolley to move the supporting device in a vector relative to the desired location in at least a first velocity only if a magnitude of the vector between the element of the crane system and the desired location is greater than a cut-off threshold, wherein the at least a first velocity is substantially constant; and
- an input shaper module manipulating the velocity command signal mapped by the on-off controller module to dampen payload oscillations when the crane trolley is accelerated or decelerated.

2. The crane control system of claim **1**, wherein the element of the crane system is the crane trolley and the position signal is indicative of a horizontal planar distance between the crane trolley and the desired location.

3. The crane control system of claim **1**, wherein the locator device is portable.

4. The crane control system of claim **1**, wherein the cut-off threshold is determined as a function of acceleration and/or deceleration properties of the crane trolley.

5. The crane control system of claim **1**, wherein the cut-off threshold is determined as a function of one or more parameters of the payload.

6. The crane control system of claim **5**, wherein the one or more parameters of the payload are chosen from the group consisting of weight of the payload, length of the payload, width of the payload, height of the payload, geometrical shape of the payload, and material of the payload.

7. The crane control system of claim **1**, wherein the cut-off threshold is determined in conjunction with one or more properties of the input shaper module.

8. The crane control system of claim **1**, wherein the cut-off threshold is determined as a function of a vector position of the desired location with respect to the crane trolley.

9. The crane control system of claim **1**, wherein the at least a first velocity is equal to the first velocity if a magnitude of the vector between the element of the crane system and the desired location is greater than the cut-off threshold and less than or equal to an intermediate threshold, and the at least a first velocity is equal to a second velocity greater than the first velocity if the magnitude of the vector between the element of the crane system and the desired location is greater than the intermediate threshold.

10. The crane control system of claim **1**, wherein the real-time position-location module uses characteristics of ultra-wide-band radio-frequency signals that are emitted by the locator device and received by a plurality of sensors.

11. The crane control system of claim **1**, wherein the desired location is the location of the locator device.

12. In a crane system comprising a crane trolley and a supporting device for carrying a payload, a radio-frequency-based crane control system, comprising a real-time position-location subsystem, comprising:

- a portable locator device emitting ultra-wide-band radio-frequency signals in response to an input;
- a plurality of sensors positioned at known locations and receiving the ultra-wide-band radio-frequency signals; and
- a real-time position-location module using the received ultra-wide-band radio-frequency signals to generate a position signal indicative of a horizontal planar distance between the crane trolley and the portable locator device;
- an on-off controller module mapping the position signal to a velocity command signal, wherein the velocity command signal comprises instructions for the crane trolley to move in a vector relative to the locator device in at least a first velocity only if the horizontal planar distance

between the crane trolley and the locator device is greater than a cut-off threshold, wherein the at least a first velocity is substantially constant; and

an input shaper module manipulating the velocity command signal mapped by the on-off controller module to dampen payload oscillations when the crane trolley is accelerated or decelerated.

13. The radio-frequency-based crane control system of claim **12**, wherein the cut-off threshold is determined as a function of acceleration and/or deceleration properties of the crane trolley.

14. The radio-frequency-based crane control system of claim **12**, wherein the cut-off threshold is determined as a function of a vector position of the locator device with respect to the crane trolley.

15. The radio-frequency-based crane control system of claim **12**, wherein the cut-off threshold is determined as a function of one or more parameters of the payload.

16. The radio-frequency-based crane control system of claim **15**, wherein the one or more parameters of the payload are chosen from the group consisting of weight of the payload, length of the payload, width of the payload, height of the payload, geometrical shape of the payload, and material of the payload.

17. The radio-frequency-based crane control system of claim **12**, wherein the cut-off threshold is determined in conjunction with one or more properties of the input shaper module.

18. The radio-frequency-based crane control system of claim **12**, wherein the at least a first velocity is equal to the first velocity if the horizontal planar distance between the crane trolley and the locator device is greater than the cut-off threshold and less than or equal to an intermediate threshold, and the at least a first velocity is equal to a second velocity greater than the first velocity if the horizontal planar distance between the crane trolley and the locator device is greater than the intermediate threshold.

19. A method of controlling a crane system, comprising:

generating a position signal indicative of a vector between a desired location and an element of the crane system;

mapping the position signal to a velocity command signal, wherein the velocity command signal comprises instructions for the crane trolley to move in a vector relative to the desired location in at least a first velocity only if the magnitude of the vector between the element of the crane system and the desired location is greater than a cut-off threshold, wherein the at least a first velocity is substantially constant;

manipulating the velocity command signal to dampen payload oscillations when the crane trolley is accelerated or decelerated.

20. The method of controlling a crane of claim **19**, wherein the cut-off threshold is determined as a function of acceleration and/or deceleration properties of the crane trolley.

21. The method of controlling a crane of claim **19**, wherein the cut-off threshold is determined as a function of a vector position of the locator device with respect to the crane trolley.

22. The method of controlling a crane of claim **19**, wherein the cut-off threshold is determined as a function of one or more parameters of a payload.

23. The method of controlling a crane of claim **22**, wherein the one or more parameters of the payload are chosen from the group consisting of weight of the payload, length of the payload, width of the payload, height of the payload, geometrical shape of the payload, and material of the payload.

24. The method of controlling a crane of claim **19**, wherein the cut-off threshold is determined in conjunction with manipulating the velocity command signal.

25. The method of controlling a crane of claim **19**, wherein the at least a first velocity is equal to the first velocity if the magnitude of the vector between the element of the crane system and the desired location is greater than the cut-off threshold and less than or equal to an intermediate threshold, and the at least a first velocity is equal to a second velocity greater than the first velocity if the magnitude of the vector between the element of the crane system and the desired location is greater than the intermediate threshold.

26. The method of controlling a crane of claim **19**, wherein the desired location is the location of a locator device.

27. The method of controlling a crane of claim **26**, wherein the step of generating a position signal uses characteristics of ultra-wide-band radio-frequency signals that are emitted by the locator device and received by a plurality of sensors.

28. The method of controlling a crane of claim **19**, wherein the element of the crane system is the crane trolley and the position signal is indicative of a horizontal planar distance between the crane trolley and the desired location.

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